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STUDIES TO ENABLE A PARADIGM SHIFT IN THE SPACE ENTERPRISE: ASTRO/ORBITAL EXPRESS

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Final Report

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This report has been approved for publication.

//signed//

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Project Manager

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14. ABSTRACT

This report reviews the work done on the no-cost extension on the on orbit servicing studies. The first task was to extend the detailed communication satellite studies to the military case where the value function does not bear the linear relationship between revenues and costs. The second task was to write up all the on orbit servicing studies (OOS) in the form of an extended monograph. The first task was accomplished through the work of two students. Adam Ross showed how to extend the MATE-CON work on helping decision makers make choices from the static case where attributes are defined initially and stay the same to the dynamic case. In the dynamic case, the decision maker preferences may change with time or the decision makers may have unarticulated preferences (typically expressed as a desire for flexibility). This allows us to move from the case of commercial communication satellites (which have well articulated fixed attributes) to the military case where the preferences can change over time. In the work of Matt Richards, a systematic taxonomy has been developed for analyzing which military space system architectures makes sense for OOS.

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Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration

Adam M. Ross, MIT ESD PhD Candidate

This work extends the value-centric, decision theoretic tradespace exploration framework developed by the author in his Masters thesis by adding an expanded understanding of value, dynamic contexts, and system change.[1]

Classes of Value: From Articulated to Unarticulated

Spectrum of Perceived Needs

The value created by a developed system can often be placed into two categories: driving need, or derived need. Driving need exists before the system is developed and provides the impetus for the development effort. Derived need emerges from the system in operation, revealing itself to those affecting and affected by the system. From the perspective of the initial system Designer who seeks to create a valuable system, the driving need is often expressed in terms of objectives and requirements, while the derived need is expressed through marketing research and business strategy. A key difficulty presented by derived needs to the Designer is the uncertainty associated with it. Instead of viewing the needs in terms of these two categories of driving and derived, a more useful taxonomy is to consider value as a spectrum of needs from articulated to unarticulated.

Imagine there exists a set of needs for every system stakeholder past, present, and future. If a system designer could know these needs and provide a way for the system to meet them in the correct manner at the correct time, such a system would be valuable indeed. Articulated needs are those needs from the set that have been explicitly communicated to the system Designer. Unarticulated needs are those that have not yet been explicitly communicated. The reasons for the unarticulated needs are various, but the goal of the Designer is the same: discover as much of the unarticulated needs as possible, or at least make it so the system can meet them when they are revealed or discovered.

Unarticulated needs include those that cannot be explicitly communicated because the stakeholder has forgotten them for the moment, or does not yet know them, or cannot quite express them in words. Unarticulated needs also include needs that stakeholders do not say because the stakeholder has assumed that the Designer is already aware of them. Additionally, unarticulated needs include those needs the stakeholder will not say because, for whatever reason, those needs must remain secret. The reasons for the unarticulation may change over time as well.

The process of revelation or discovery of unarticulated needs can incorporate several methods including personal reflection, conversations with mediators, experience with the system, interactions with the system context, or seeing the system in a changed or new context.

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[1] Ross, Adam M. *Multi-Attribute Tradespace Exploration with Concurrent Design as a Value-Centric Framework for Space System Architecture and Design.* Dual-SM, Aeronautics and Astronautics, and Technology and Policy. Massachusetts Institute of Technology: 2003.

Role of Dynamic Context

A common approach in system design is to optimize the system according to a set of objectives. Finding the "best" system is the goal of such an exercise. The technocratic optimization approach works well and will provide the "best" answer only if the assumptions of the analysis hold true in the real world. Unfortunately, often such is not the case. A fundamental assumption in the optimization approach is the assumption of correct objective functions. If the objective functions change with time, no guarantee exists that the system will remain "best". In fact, recent research suggests that such overly optimized designs are quite fragile in the face of changing objectives or context.

Related to the assumption of static objectives is that of static context. Design for robustness is an approach to try to find design options that will continue to perform well in the face of changing operational environments. The context includes not only the operational environments however, but also the stakeholder sets, the expectations of the system, the resources available to the system, the competition for the system, and any other exogenous factor that affects the perceived value of the system. Many of these factors are not considered during an optimization exercise beyond the technical environment, though they may significantly affect the perceived value of the system. An example of such a dangerous omission is a technical optimization of a satellite-based communication system, ignoring terrestrial competition, such as the fate suffered by the Iridium and Globalstar systems.

In the military regime, high-level objectives may remain relatively static, such as 'defend some region,' or 'provide information about some region.' As these objectives are decomposed, however, assumptions begin to creep in, which also inherently includes the possibility for change. An example is the emerging usage of UAVs for both rapid reconnaissance and interdiction, or the growing civil dependence on the military GPS system. On even shorter time scales, targets of opportunity arise and systems must react quickly in order to deliver value, even if the desired usage does not match the intended usage. In order to capture value, as it emerges from unarticulated to articulated space, systems must be designed for changeability.

Changeability Defined

Changeability relates fundamentally to the often-discussed system properties of flexibility, adaptability, scalability, and robustness, among others. These properties all have one thing in common: they relate to how the system can change with time.

Two related tensions through the value discussion are the interplay between the stakeholders with their need, and the Designers with their system. The need of the stakeholders can be captured in the value-space perspective on the system. The system of the Designer can be captured in the real-space perspective on the system. The key differentiator between these spaces is that the real-space represents tangible elements of the system that can be actively manipulated by the Designer (design variables), while the value-space represents intangible or tangible aspects of the system from which stakeholders derive value (attributes).

Real-space ilities

The system properties that relate to the real-space perspective are flexibility, adaptability, and rigidity. Flexibility is the ability of the system to be changed by an external agent. Adaptability is the ability of the system to be changed by an internal agent. Rigidity is the inability of the system to be changed. The external versus internal agent boundary is determined by the boundary of the system. The ability versus inability for system change is determined by the boundary of ‘cost’ (money or time, or other resource) that is acceptable to the desirer of change.

Value-space ilties

The system properties that relate to the value-space perspective are scalability, modifiability, and robustness. Scalability is the ability of the system to have the level of a currently displayed attribute changed. Modifiability is the ability of the system to have the currently displayed attribute set changed, including the addition or deletion of new or old attributes. Robustness is the ability of the system to continue to deliver value in the face of a changing context.

Forming ility statements

In order to properly pose the question “is my system flexible?” it is necessary to formulate a rigorous statement. First, the subjective scale for acceptable resource usage must be set (boundary of ability versus inability to change). Second, the origin of change must be chosen (will it be an external or internal or no agent?). Third, the value-effect change must be chosen (level or attribute set, or constant value?). An example: Is my system flexibly scalable in bandwidth for less than $10M and less than three months? This formulation can be answered more meaningfully than the more nebulous “is my system flexible?”

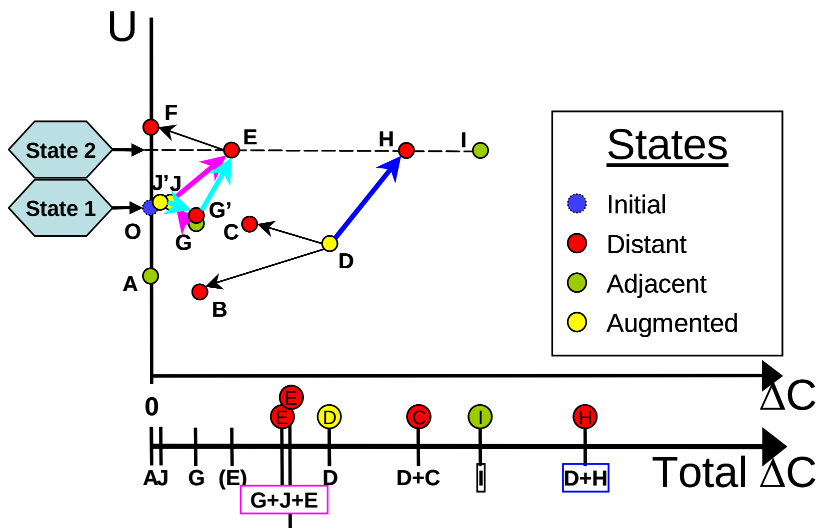
A Method to Assess System Changeability

Once the philosophy of changeability has been related and understood by the Designer, analysis techniques must be augmented in order to assess the changeability of system design options.

Including Transition Paths

Designing ‘in’ the changeability of the design variables (real-space change) includes the notion of transition paths. A transition path is the mechanism for changing a system from one state to another state. The time and cost for the change is highly dependent on the mechanism employed (a path dependence for the system transitions). When a designer is enumerating the space of system options (tradespace), part of the exercise must include consideration for change. Thus, in addition to creating the design variables (the quantification of the system designs), the Designer also creates transition mechanisms, or rules. These rules specify the allowed changes from design to design and provide a mechanism for calculating the ‘cost’ for following the rule.

An example of applying such an approach is the following: Consider a system design for a satellite in low earth orbit whose orbit must be changed, for whatever reason, but whose fuel must remain at pre-orbit change levels. Possible transition rules include: 1) burning on-board fuel to maneuver to a new orbit, followed by an on-orbit refuelability modification, and on-orbit refueling to bring the on-board fuel back to pre-burn levels, 2) adding the refuelability modification prior to launch, burning the on-board fuel to maneuver to a new orbit, followed by on-orbit refueling to bring the on-board fuel back to pre-burn levels, 3) using a space tug to grab the satellite, move it to the new orbit, and release, 4) purchase a new satellite that is inserted into the correct new orbit. Figure 1 shows how these four path mechanisms result in different costs for having a system change from the same state 1 to state 2. The points are plotted in terms of each state’s incremental cost over the previous state (ΔC) and its perceived value (Utility, U)



Paths

Goal DV Change	Mechanism	Δ Cost	Type	Example "points"
↓Perigee	↓Delta V	Gx	Adjacent	O→G
↑Delta V	Add Refuelability	Jx	Augmented	G→J
↑Delta V	Refuel	Ex	Distant	J→E
↑Delta V	Add Refuelability	J'x	Augmented	O→J'
↓Perigee	↓Delta V	G'x	Distant	J'→G'
↑Delta V	Refuel	Ex	Distant	G'→E
↓Perigee	Add Tug	Dx	Augmented	O→D
↓Perigee	Use Tug	Hx	Distant	D→H
DV reset	Purchase new system	Ix	Adjacent	O→I

Figure 1 Example Transition Paths for Changing from State 1 to State 2 (Perigee lowering)

Technology and creativity are the key factors affecting the creation of transition mechanisms. In fact, the process of trying to develop transition mechanisms can elucidate key areas where technology development can greatly increase the changeability of a design (by either enabling new transition paths, or reducing the 'cost' of an existing path.)

The creation of Orbital Express, or other standardized on-orbit servicing architectures, is an explicit effort to create transition mechanisms (using the standard servicing architecture) at lower cost and time, thereby increasing the changeability of systems that adhere to the architecture standards. The reduced transition costs for the serviceable systems come at the price of increased development costs. Finding the proper balance between initial cost increases and reduced changeability costs can be analyzed in a tradespace analytic framework. Non-serviceable systems can be compared on the same utility-cost plots to serviceable systems. All other things being equal, a serviceable system will probably have higher cost at a fixed utility, or lower utility at a fixed cost. The benefit for a serviceable system, however, will be captured when adding in the potential transition paths for that system in the tradespace.

Computers can automate the path analysis to enable large tradespace exploration by incorporating the idea of transition rules. The rules are automatically applied to the tradespace in order to create a tradespace network linked through transition paths. More changeable options will manifest more possible transition paths to other designs. The "costs" of these transitions are embedded in the arcs connecting the design options. In order for this analysis to be truly useful, however, the temporal context for the changeability analysis must be added.

Adding the Timeline

Each of the static analyses done prior can be envisioned to be a single frame of a long movie, which strung together, can form a dynamic picture of the system. An Epoch is the single frame short run analysis, during which a scenario is defined. The objectives, constraints, stakeholder set, duration, and boundary conditions are specified. The previous example of changeable tradespace analysis can be conducted during each Epoch. When one of the criteria of an Epoch changes, a new one should be created and analyzed (for example, the change of a policy, market conditions, stakeholder set, or objectives). A string of Epochs with satisfied boundary conditions (continuity of states across the boundary) forms a system Era. The system Era is the long run picture of the system. Figure 2 shows a notional System Era consisting of *n* Epochs.

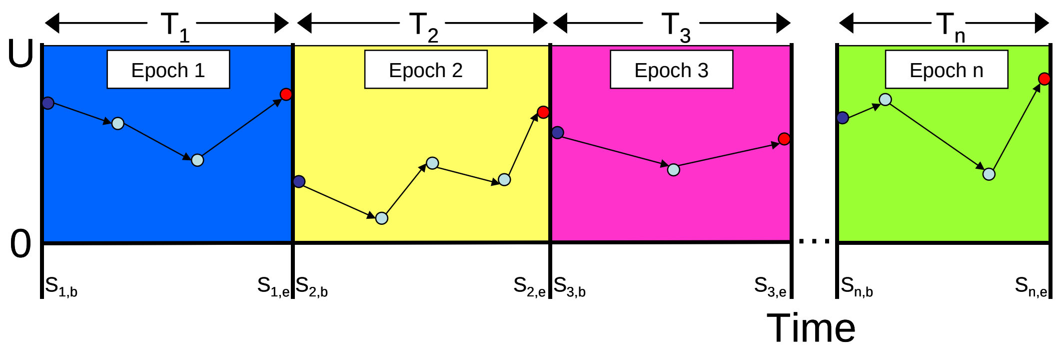


Figure 2 System Epochs and System Era: The System Change Timeline

Changeability can be assessed during an Epoch or across an Era, depending on the desired system property to be determined (i.e. scalability in bandwidth in the short run or long run).

Example Application to On-orbit Servicing

As an example of the proposed analysis framework, suppose a system designer is planning to develop a new space system. Proposed design options include traditional designs, as well as new standardized Orbital Express accessible designs, which can be more readily changed. Such changes include restoring and upgrading capabilities of the system. Figure 3 depicts a time-series tradespace analysis of the problem. Each utility-cost tradespace shows the Designer various design options in terms of their perceived value (Utility) and cost. The "optimal" designs are those that deliver maximum value at a given cost. Both serviceable (red) and non-serviceable (light blue) designs are compared. Over time, the perceived value of the system may change, moving the "optimal" designs into sub-optimal regions of the tradespace. The figure shows three notional time periods, differentiated by differing value functions. Serviceable designs can be transitioned to other designs at relatively low cost, especially as compared to traditional non-serviceable designs, thereby enabling the system to recapture lost value over time. Given the ability to move toward the higher value solutions over time, the Designer selects a serviceable option and compares its time-varying value-delivery to a similar non-serviceable option.

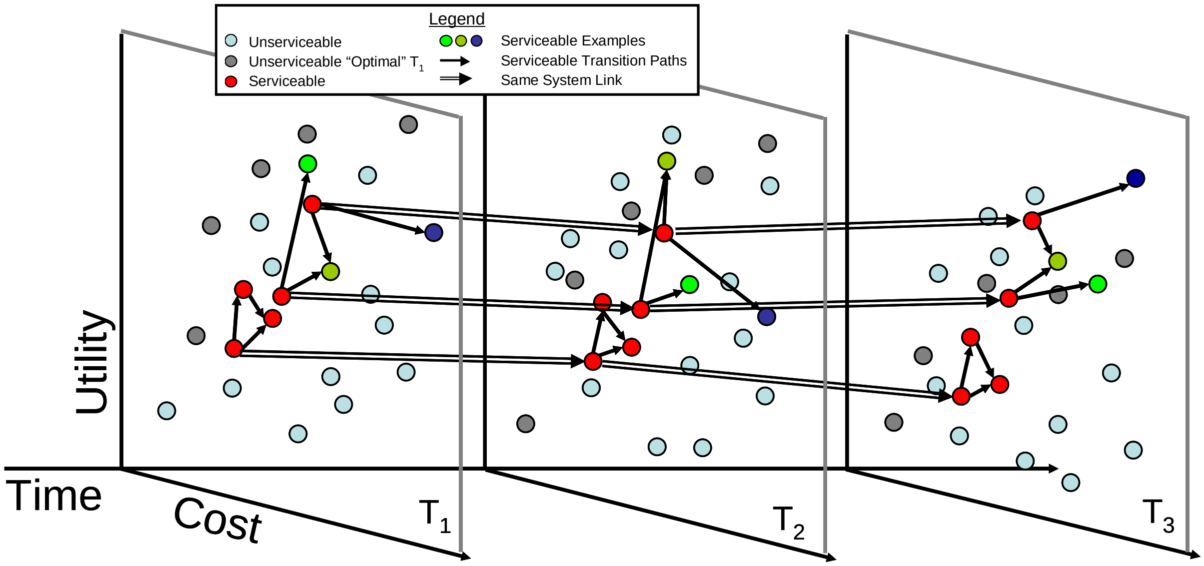


Figure 3 Time-series Tradespaces with Serviceable Options (notional)

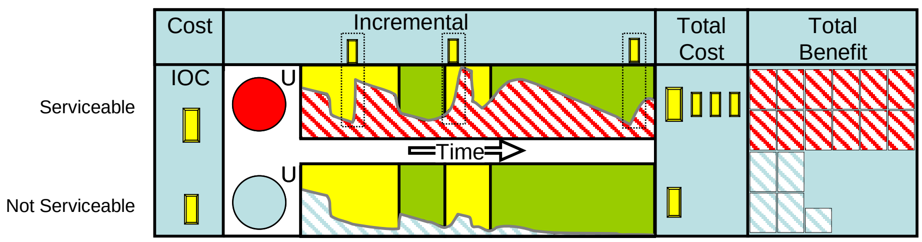


Figure 4 Temporal Comparison of Serviceable vs. Non-serviceable Systems

Figure 4 gives another view of the dynamic recapturing of value allowed by a serviceable design. Incremental costs are incurred by the serviceable system each time a servicing mission is performed (a system change). While the total system cost for a changeable system will most likely exceed that of a static system, the total system benefit may warrant such an approach. (Iso-benefit comparisons of cost, or iso-cost comparisons of benefit will yield even more insights into which approach may be better.) Given this analysis, the Designer next seeks to see how a changeable system might be depicted over its system timeline.

Figure 5 gives an example of a system timeline for a serviceable system. Such a system has both variable value delivery due to performance changes, as well as due to changing value perceptions (e.g. new markets, targets of opportunity, etc.). Servicing events enable the system to both capture and recapture value in the dynamic context.

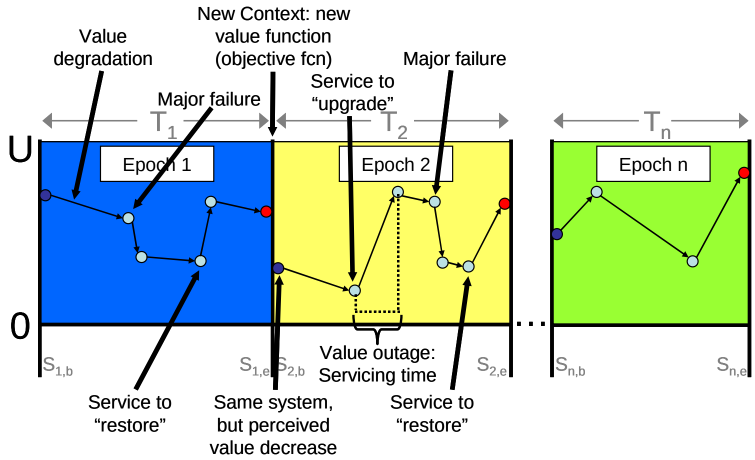


Figure 5 System Timeline Showing the Effects of On-orbit Servicing on a System (notional)

Systems that are designed for servicing (changeability) will likely have lower physical change costs than traditional systems and, by the definitions given above, will more likely be perceived as flexible (ie, changeable.) Designers of Orbital Express should keep in mind the subjective thresholds for acceptable change costs for potential decision makers. Even if the costs are less than traditional designs, if those costs are higher than the threshold, servicing will not occur and the system will be perceived as rigid. Scenario analyses of likely value-perception changes should be done to determine whether physical alteration of the satellite is the most cost-effective mechanism for changing a system. It is possible that the most value-generating changes could come about through clever functional allocation at the time of system design, coupled with low-cost software, or other non-physical upgrades.

Discussion

One implication of the framework is that changeability, including the concept of flexibility, does not necessarily require physical change. Change is desired in order to match the system with revealed unarticulated value (i.e. with the articulation of needs over time). The need that is articulated may already coincide with existing system capabilities, or perhaps with only slightly modified system capabilities. This suggests that systems with a more generic set of capabilities may have more potential value, since those capabilities can be recombined into a potentially very large set, which may have a higher likelihood of overlapping revealed value.

Realizable changeability must address the 'cost' of matching system capabilities to revealed value. Concepts such as modularity and standards are specific approaches to reduce the potential 'cost' of a change at the moment of change execution. A common complaint of these approaches is their upfront investment cost with no guarantee of use (unused change options). The future is not necessarily predictable, so the possibility of unused options will inevitably remain. Nonetheless, change is predictable in that it *will* happen at some point. The role of a good system designer is to recognize when it is worthwhile to build in the ability for the system to change with its context in order to remain of value. The analysis methods mentioned above will help the Designer in system design trade studies develop lower 'cost' opportunities for both short and long term changeability, both before and after the system is fielded.

Task 1: Research Title: On-Orbit Serviceability of Space System Architectures
Student: Matthew Richards
Master of Science degrees in Aerospace Engineering, Technology and Policy

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<u>Introduction</u>
Space systems are critical to maintaining international security, economic progress, and safety from natural disasters. Unfortunately, the current paradigm of space system conceptual design, acquisition, and operation is failing. Traditional systems engineering processes are not applicable to the conceptual design of system-of-systems into which satellites are increasingly integrated. Space system acquisitions are often characterized by tremendous cost overruns and schedule slips. And satellite operations are tightly constrained by the physical inability to access hardware post-launch. There is a need for holistic reform that targets the entire space enterprise rather than locally optimal solutions. Most fundamentally, research is needed to overcome the current deficiencies of space system conceptual design, acquisition, and operation by proposing and demonstrating the value of a more flexible approach.

This research addresses these problems by assessing the amenability of satellites to on-orbit servicing and exploring the value of architecture frameworks as tools for completing such analyses. On-orbit servicing (OOS) has been proposed to enable satellite operators physical access to their systems after launch—addressing the established paradigm of inflexible, unresponsive space operations. Existing OOS studies focus on the development of servicing provider architectures or case studies in customer valuation of various servicing missions. The focus of this research is on the physical amenability to OOS—or serviceability—of all space system architectures.

Figure 6. Artistic representation of servicing vehicle

The goals of this research are two-fold: contribute theoretically by proposing a generalized process for assessing system serviceability and contribute practically by testing this process through application to all operational satellite systems. Specific research objectives include:

1) Characterize the current state of architecture frameworks
2) Develop a framework to describe the serviceability systems

3) Categorize space systems within the framework
4) Identify architectural elements across space systems that make them physically amenable to on-orbit servicing
5) Investigate political, legal, operational, and financial context for OOS

Development of an Ordered Taxonomy of Space System

Architecture frameworks for physical systems have been developed by the Department of Defense and the UK's Ministry of Defense to add structure to the problem of designing and acquiring system-of-systems. By characterizing the form, function, and rules governing systems, architecture frameworks serve as a communication tool to stakeholder communities with different views of the system and facilitate comparative evaluation across architectures. This research will employ and potentially propose improvements to the Department of Defense Architecture Framework (DoDAF) to conduct serviceability assessments across space systems.

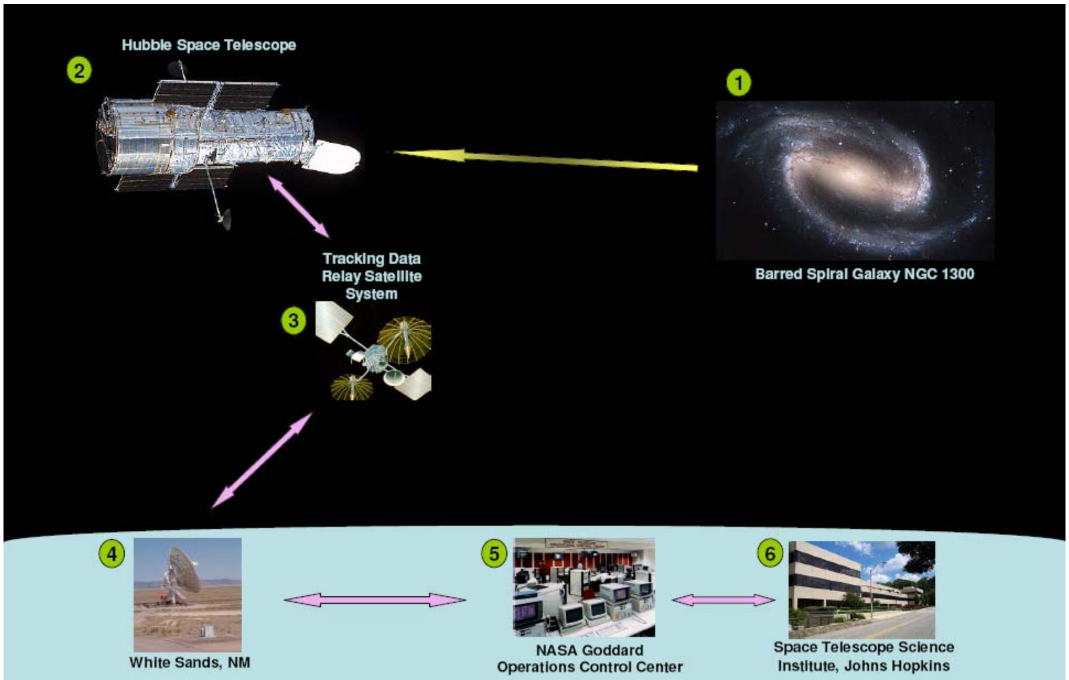

Figure 7. DoDAF OV-1: High-Level Operational Concept Graphic, Hubble Space Telescope

The application of architecture frameworks to physical systems is relatively new. The UK's Ministry of Defense Architecture Framework (MoDAF) is still in development while the DoDAF in its current form is a series of templates describing static products.

Methodology to Assess Physical Amenability of Satellites to On-Orbit Servicing

This research will propose a generalized process for assessing serviceability. Work on this methodology is an on-going activity. Currently, complexity theory is being consulted as a potential theoretical basis for identifying fundamental attributes of servicing systems. Lessons learned from servicing other systems which are technologically enabled and hard to access—such as off-shore oil platforms—will also be explored. Hypothesized fundamental attributes of servicing include Knowledge, Scale, Precision, and Timing requirements across four servicing activities: Rendezvous, Acquire, Access, and Add Value.

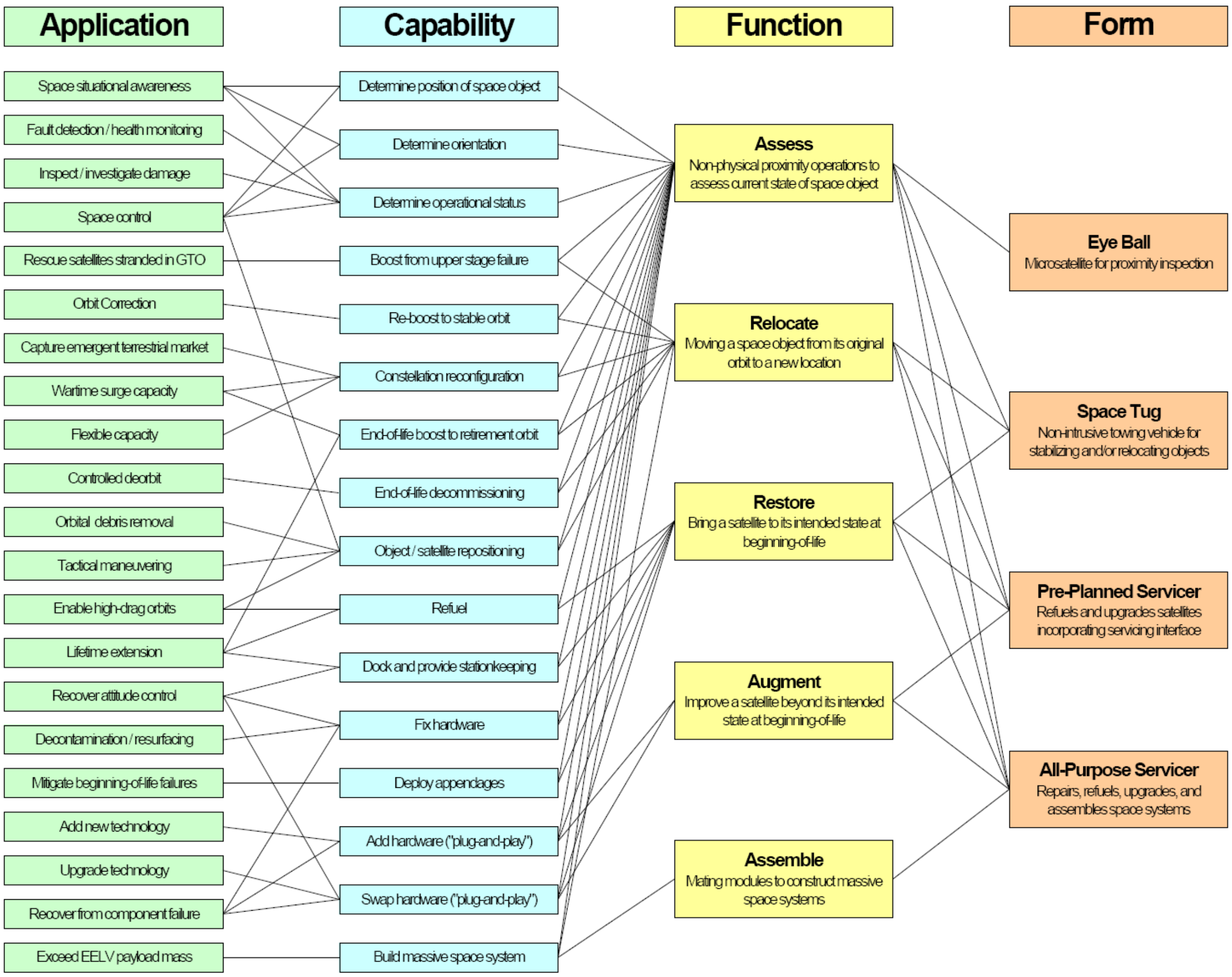

Figure 8. Mapping of on-orbit servicing functional decomposition to physical systems

Upon establishing a "menu" of serviceability metrics, potential servicing mission areas will be functionally decomposed. The figure above displays a "spiral one" iteration of high-level servicing functions mapped to lower-level capabilities and traced to specific applications. This research will propose a serviceability function for each servicing mission area defined above, deriving input variables from the "menu" of serviceability metrics.

In order to maximize the number of satellites assessed for physical amenability to on-orbit servicing, global satellite databases will be consulted. Of particular note is the Union of Concerned Scientists (UCS) Satellite Database which contains information on the over 800 operational satellites in orbit around the Earth. Technical information about each satellite includes mass, power, launch date, and expected lifetime in addition to orbital elements, user information, and general purpose. Our preliminary assessment is that the UCS Satellite Database will be a useful source of input data to a low-fidelity model of serviceability—serving as a filter to down select to a short list of serviceable satellites. High-fidelity models will be employed to assess serviceability across the short list of satellites deemed serviceable. We will attempt to employ the static views of space systems captured in architecture frameworks as the input data to these higher fidelity models.

Architecting for Satellite Servicing: Prescriptive Technical Considerations

The key output of this research will be a set of architectural heuristics for designing serviceable spacecraft. We have hypothesized that for satellites to be serviceable, the servicing provider will have high levels of knowledge of the state of the system (*e.g.*, high-fidelity telemetry, configuration control during assembly, orbits with 'less' radiation and thermal cycling, orbits where the satellite might be inspected). Serviceable satellites might also minimize precision required in servicing activities through a modular architecture and docking interfaces which guide autonomous rendezvous and docking.

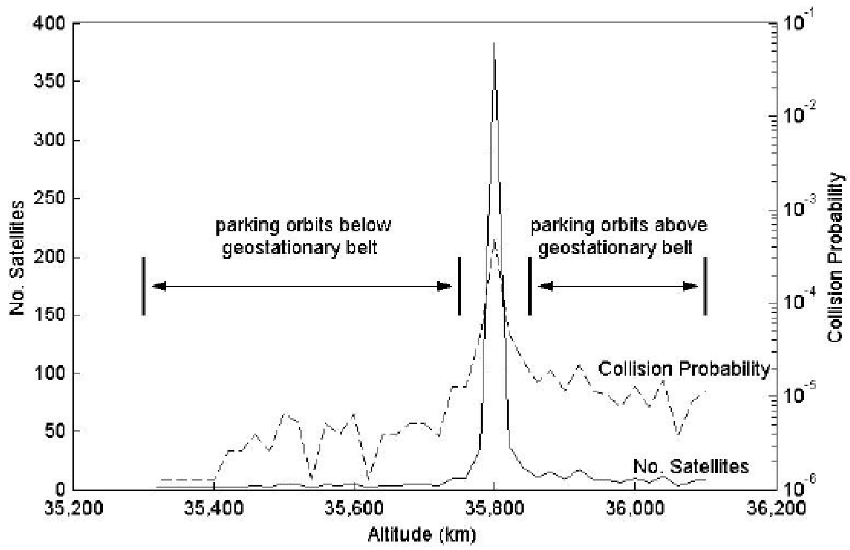

Figure 9. Collision probabilities for various geosynchronous servicing vehicle parking orbit altitudes

In addition to prescribing architectural features that make satellites more serviceable, this research will also consider technical issues associated with the servicing vehicle. For example, estimates of collision probabilities for a near-GEO servicing vehicle parking orbit were calculated using the Poisson distribution and principles of the kinetic theory of gases (see above). A ten year servicing vehicle lifetime was assumed. The velocity change (ΔV) requirements to reach geosynchronous altitude vary between 1.8 m/s and 16.6 m/s depending on the altitude change necessary. Propulsion choice (*i.e.*, chemical vs. electric) affects the time requirements for transfer from parking to geosynchronous orbit. The time required for transfer via electric propulsion can range to as high as 180 days, depending on the acceleration produced by the engine, while the transfer time via chemical propulsion is approximately 12 hours over the range of possible parking orbit altitudes.

The advantage of low thrust electric propulsion systems with specific impulses exceeding 1,000 seconds is a combination of reduced tug mass and increased ΔV capability. On the other hand, because of the slow, spiraling trajectory followed when changing altitude, the servicing vehicle would orbit repeatedly at altitudes where the probability of collision is heightened slightly. In addition, the power requirement for electric propulsion systems, ranging from 0.5 kW up to 4.5

kW, is much higher than for chemical propulsion. It should be noted that even if a servicing vehicle were equipped with electric, chemical thrusters would still be required for maneuvers in close proximity to the target spacecraft.

Political, Legal, and Financial Challenges of On-Orbit Servicing

This research also addresses the political, legal, and financial context of on-orbit servicing. Although servicing technology will likely be developed in accordance with U.S. Space Transportation Policy, the actual deployment of such a system is uncertain due to the nature of its potential customers. The primary policy challenge facing implementation of a servicing system is gaining the trust of satellite operators. This challenge is particularly great in the Air Force, where program managers of national space assets are traditionally risk-adverse and might hold a short-term outlook of satellite operations given that the tenure of many military program managers is less than two years. To overcome this barrier, it might be necessary to review the incentive structure of Air Force program managers. Lengthening tours-of-duty of program managers or providing career incentives to program managers who extend mission life of space assets are possible improvements. Another alternative is to make mission life extension a requirement for high-value space assets.

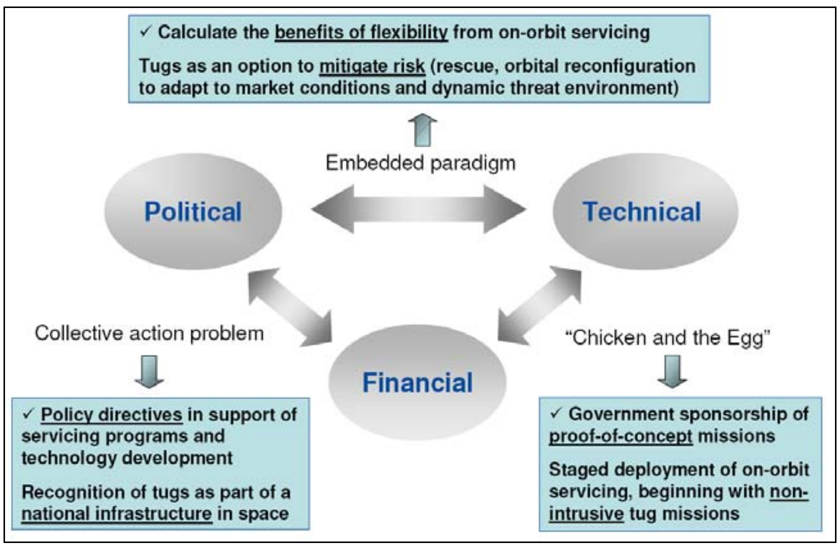

Figure 10. Meeting the implementation challenges of on-orbit servicing

Legal constraints for space tug operations can be divided into two categories: customary international law and national law. Since its establishment in 1959, the United Nations Committee on Peaceful Uses of Outer Space (COUPOS) has launched five major international legal instruments that form the bulk of laws governing space. Key principles pertinent to satellite servicing include a state's right to maintain jurisdiction and control over space objects (regardless of condition), registration obligations, and on-orbit liability. Other customary international space laws are derived from bilateral arms control treaties between the U.S. and U.S.S.R. National legal principles relevant to space tug operations include U.S. criminal law pertaining to interference with the operation of a satellite.

Government-commercial cost sharing precedents exist for space assets and other shared resources. However, it is unclear what type of financing model servicing operations will assume or how the issue of proprietary development will impact financing. The Commercial Space Competitiveness Act of 1992 authorized NASA and other agencies to make their facilities available to private entities. This provides a number of options for ownership, operation, and use of a satellite servicing system.

Task 2: The OOS studies in a monograph; an example

Running Example two: general purpose orbit transfer and servicing vehicle (SpaceTug)[i]

The SpaceTug project was carried out by a team of undergraduate and graduate students, postdoctoral and staff researchers, and faculty in a single summer. It was the first use of the MATE-CON method under contract with a government sponsor. The aim was to explore the tradespace of possible orbit transfer and service vehicles, looking for potential cost-effective capabilities that might be of national interest.

The space tug concept is for a vehicle or vehicles to loiter in earth orbit and carry out multiple missions involving visiting existing assets in orbit and observing, servicing, or moving them. The project was motivated by a general interest in such systems as a national capability, and the historically poor results when proposing such systems for specific missions without looking at the wider tradespace of possible uses and designs.

Figure 11 shows the MATE process as carried out for the SpaceTug project. The project was scoped widely, as the possible uses for such a system are not currently know. A somewhat simplified version of the MATE method was used. The method was adapted in response to difficulties including the lack of an immediate customer and a very open design space. The customer utilities were handled parametrically to understand the sensitivities of the tradespace to ranges of, and changes in, user needs. The analysis was done at a high level, using low-fidelity models, but covering a large range of possible designs.

The capabilities of a SpaceTug vehicle determined to be useful to a potential user include: (1) total delta-V capability, which determines where the SpaceTug can go and how far it can change the orbits of target vehicles; (2) mass of observation and manipulation equipment carried, which determines at a high level what it can do to interact with targets, referred to here as its *capability*; and (3) response time, or how fast it can get to a potential target and interact with it in the desired way.

These attributes are translated into a single utility function. In the absence of real users from which to collect more sophisticated functions, it was decided that a simple function that could be explored parametrically was most appropriate. The utility was a weighted sum of utilities from the three attributes above, with the weights being considered parametically. The figure shows a single-attribute utility for Delta-V. In this case, utility is assumed to increase linearly with delta-V, with diminishing returns above the levels necessary to do Low Earth Orbit (LEO) to Geosynchronous Earth Orbit (GEO) transfers.

A set of design variables (in MATE parlance, a design vector) was selected to represent possible tug vehicles. The following variables were selected: (1) observation and manipulator system mass; (2) propulsion type; and (3) mass of fuel carried.

For the simulations, simple parametric relationships and design rules were used to compute the spacecraft characteristics. These were carried out on an Excel spreadsheet. The calculations took only seconds, and were repeated for a wide variety of presumed user utilities.

The results revealed key constraints, trades, and promising types of designs. Chemical fueled tugs were severely limited, especially for higher-energy missions such as GEO transfer rescues, by the specific impulse of the fuel. Alternate propulsion concepts had other limits: electric propulsion (which is slow) was highly sensitive to the assumed utility of timely response, and nuclear propulsion results in high base costs. Independent of propulsion system, low weight grappling, observation, and control equipment was always desirable.

The tradespace analysis reveals three classes of potentially useful space tug vehicles. The Electric Cruiser occupies the “knee in the curve” for our nominal utilities, providing good value for cost. The “Nuclear Monster” is only design that can meet a desire for a high delta-V, high capability, rapid response system; electric monsters (not shown) might be interesting to users not interested in rapid response time. A final range of vehicles occupies the lower left region of the Pareto front. These are cost effective vehicles build using existing technology (e.g. storable bi-propellant systems) that can do a variety of jobs requiring lower delta-V. They could, for example, tend set of vehicles in similar orbits, doing a variety of maintenance tasks. For this reason (and to extend the naval support vessel metaphor) they have been dubbed “Tenders.”

The MATE trade space was used to drive an ICE session to design a variety of tug vehicles. Several “cruiser” vehicles were designed. From on or near the Pareto front, electric cruisers such as the one shown in **Error! Reference source not found.** were designed. High delta-V chemical propulsion vehicles are not optimal according the MATE analysis; the ICE results (which had difficulty closing because of extreme fuel loads) helped to illustrate why. Finally, a variety of Tender vehicles were designed; some for specific missions and some for generic service; these designs showed that a modular approach to tender vehicle design might be the best approach.[ii]

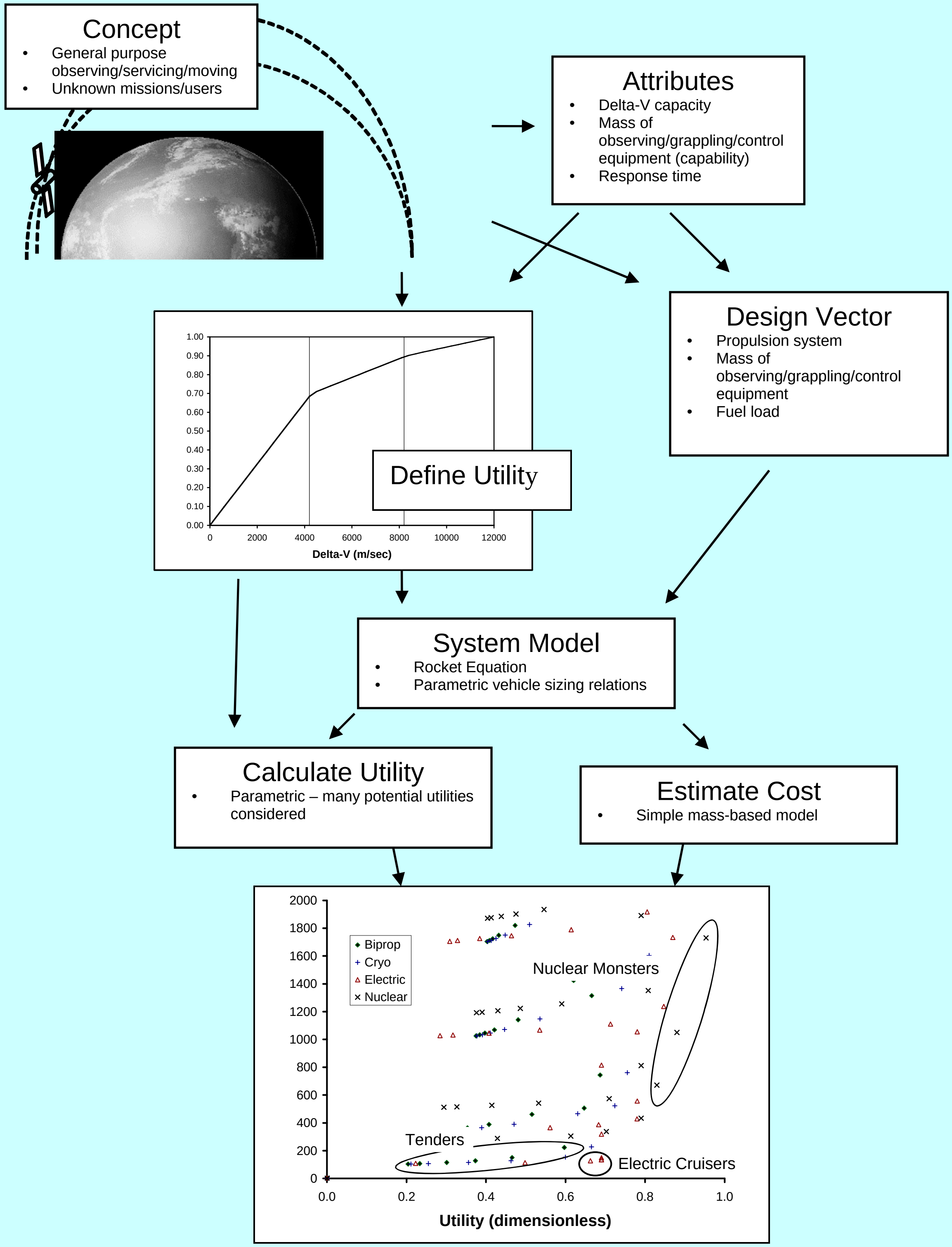

Figure 11 MATE process for SPACE TUG

Final Report for "Orbital Express Architecture and Trade Space Studies," a subcontract to Metis Design Corporation.
Hugh McManus, Principal Investigator

The work done under this subcontract was focused on the creation of a unified report or book to summarize the progress made in the Multi-attribute Tradespace Exploration (MATE) method to date, and the creation of new content as necessary to assure the relevance of this document to the problems of infrastructure systems such as Orbital Express (OE). The aim of the book is the dissemination of advanced tradespace methods. These methods will be very useful to Orbital Express and similar space infrastructure systems. They will provide a method for both the front-end design of infrastructure systems, and for consideration of the value and uses of space infrastructure when designing other systems. To assure relevance one of the two examples running through the book is a simple orbital transfer vehicle, or "space tug," of the sort that would be useful component of an OE system.

Specific tasks were carried out under this subcontract out in the context of creating the proposed book. They included:

1. Mental model for MATE application

This task involved creation of a framework for comparing MATE and conventional front-end methods. The front end of the product development process model of Ulrich and Eppinger[iii] was expanded to create a simple, intuitive "mental model" of the irreducible steps necessary to initiate a product development. Using this model, current processes and the MATE process could be compared, and the advantages of the later expressed in simple terms. The result is both a teaching tool, and a guide to understanding how MATE can be applied to areas outside of simple product design, i.e. for higher-level application such as systems architecture or system-of-systems work. It also clarifies the advantages of MATE for systems without easily defined traditional requirements, e.g. infrastructure systems.

2. Architectural applications of MATE

A study was undertaken to relate MATE to current practice in systems architecting. It has been pointed out that MATE, although it has been applied to a wide variety of systems, has primarily been used in the preliminary design of the physical architecture of space vehicles. This task attempted to clarify the use of MATE for higher-level architectural decision as well.

Architectural frameworks such as DoDAF and MODAF were surveyed. A brief description of DoDAF was included in the document, and a partial DoDAF description of the space tug system was created. The DoDAF and related descriptive tools (e.g. the CORE software) were found to be complementary to MATE analysis. A set of current practices (e.g. standards, heuristics, individual expertise, and various Systems Engineering methodologies) were also briefly surveyed. Basic difficulties with the current practice, and ways in which MATE may address them, are presented.

The mental model developed in task 1 above was used to clarify the distinctions between the preliminary design applications for which MATE has been successfully used, and the challenges at an architecture level. These will depend on the specifics of the system, but some generalizations can be made:

- If the architectural decision can be parameterized (how many vehicles to use) or reduced to discrete choices that result in different parameters in the same basic system model (what kind of propulsion to use), then the MATE method may be used "as is" for architectural trades space exploration. Simple examples of this kind have been analyzed using MATE in previous work.
- If the architecture decisions require choices that change the models used to calculate system performance (e.g. propulsion choice changes orbital calculations (electric) or vehicle dynamics (tethers)) the MATE method may be used with additional effort. Clearly, practical limits may be reached if large numbers of *models* are required. In trade space terminology, these cases involve changes to the composition (not just the enumeration) of the design vectors. In this case, the MATE method may be supplemented productively by Object-Process Methods; the work of Koo[iv] in analyzing the wide variety of Apollo architecture options is instructive.
- If the architectural decisions involve multiple stakeholders, especially if they are working at cross purposes, have poorly defined needs, or are diffuse, the MATE method is challenged. Defining meaningful objective function may be difficult. In trade space terms, the set of attributes may become large, and the set of utilities (for each attribute, for each stakeholder) may become large and incompletely defined. This problem is not intractable, but presents difficulties. There is currently no named methodology for dealing with this class of problems, although there are examples; the work of Rebentisch is instructive.[v]

3. MATE-CON method description update.

An existing description of the MATE method and associated use of concurrent engineering (-CON) was updated. Perhaps the most interesting addition was a comparison between the two running examples used in the original document, which were developed as student projects, and similar systems that have subsequently undergone detailed design and/or been launched in the real world. The remarkable agreement in both cases lends confidence in the method.

4. Integration of methods for the handling of uncertainty using MATE

This task represented the majority of the work under this contract. In the early stages of a design process, there are many uncertainties as to how technology, budgets, and user needs will evolve over the lifetime of the program. These uncertainties include both risks and opportunities; in particular, markets may change in ways favorable to a robust or versatile system. The full range of these uncertainties, their possible risks (or opportunities), mitigating (or exploiting) strategies, and possible outcomes in terms of system performance are organized in a framework developed previously by McManus and Hastings.[vi] This framework helps organize thinking about many sorts of uncertainties, but is not a tool for actually evaluating them. In this work, the framework was tied into the MATE method to provide a guide to both including uncertainties *in* the tradespace analyses, and depicting uncertainties *on* the tradespace as one of the factors that the decision-makers need to consider. The result is a *method* for handling uncertainties as part of tradespace exploration.

Understanding uncertainties is critical both to the understanding of orbital infrastructure projects (which are beset with uncertainties of all types), and for planning programs that may use orbital infrastructures. It has been demonstrated previously that a primary value created by these infrastructures is the management of both risk (downside uncertainty) and opportunities (upgrades and the like – the upside of uncertainty) for client systems.

The proposed method considers three basic aspects of uncertainty:

4a) Uncertainty IN the systems on the tradespace

The first types of uncertainty analyses proposed in the framework are the use of suitable margins (incorporated into rules of thumb in the analysis) and component reliability (e.g. Markov model) analyses. The first is an essential element of any reasonable conceptual design work. The later is sometimes either neglected or is difficult to formalize. For example, in very simple models, with "black box" models of even major components, estimating their reliability involves a fair bit of guesswork. This problem persists into more detailed models, but becomes more tractable and amenable to solution using existing tools; by the time the analysis has moved to a concurrent engineering model, a reliability "chair" should be standard practice.[vii]

If reliability is incorporated into the evaluation of the designs in the tradespace its effect will be to make the attributes of the system probabilistic; they will only be achieved at the predicted level if the system remains functional. There is some chance the attributes will be degraded or not achieved at all. For the "end user" stakeholder who defines most or all of the technical aspects of the system (at least in most cases), this probabilistic reduction in the expected value of the attribute should result in a proportional loss of utility. The cumulative effect of lost utility is to move the points on the tradespace somewhat. This movement will affect decision to the extent it is uneven – intrinsically less-reliable systems will be selected against.

Due to the assumptions made when measuring the utilities, it is methodologically unsound to treat the reliability itself as a separate attribute *for the end-user*. However, there are multiple stakeholders (e.g. career minded program managers, holders of portfolios of systems, high level planners of capabilities) for whom program reliability is an important and (for them) independent attribute. For these stakeholders, the calculated reliability needs to be considered explicitly. This is not in itself a new idea, although most previous presentations have considered reliability presented against a single metric of performance, and perhaps cost.[viii] In the MATE formulation, it becomes another attribute, although like cost one which should not under most circumstances be combined with the other attributes using multi-attribute techniques. A simple example calculation based on a small experimental satellite is used to illustrate how, for some stakeholders, reliability considerations may lead to system architectures rather different than those that seem optimal to the other stakeholders. This can set up a classic case of stakeholders with conflicting utilities, which can only be resolved through negotiation.

4b) Uncertainty depicted ON the tradespace.

More complex uncertainty effects may be represented explicitly on the tradespace. Good practice of the MATE techniques calls for technical parameters in the tradespace models to be represented not by "hardwired" values (or worse, modeling assumptions), but rather be incorporated into a "constants vector." Technological and development uncertainties thus enter the tradespace models via uncertainties in the values in this vector. This allows, at a minimum, sensitivity studies to be carried out to capture dangerous sensitivity to possibly uncertain parameters. This should be considered good practice in tradespace analysis even without further consideration of uncertainties.

More interesting is use of varying elements in the constants vector to calculate the resulting variability of the results on the tradespace. Although this could theoretically be done using statistical moment or interval methods, Monte Carlo methods are well suited to tradespace analyses. They require multiple runs of the model with various combinations of randomly-varied parameters, but these models must be efficient to be used in the tradespace analysis in the first place, so the computational effort should be tractable. The simplest way to show these on the tradespace is by distribution "clouds," although bounds or best/worst endpoints could also be used.[ix,x]

The same method may be used to express user need uncertainty by varying the elements of the multi-attribute utility model in a similar way. The space tug example is extended to include both technical and user need uncertainty, and the resulting tradespace explored. The example proves quite rich, illustrating several different kinds of technical uncertainty, and both downside risk and upside opportunity uncertainties created by uncertain user needs. As with "static" tradespace exploration, the presentation of the uncertainties is the beginning of the process of interrogating the full set of tradespace data to determine the root causes of the uncertainties. This fundamental knowledge is the real value gained by using the extended MATE method.

The proposed method would be a key tool for users of orbital services, as it highlights in the first stages of system design key uncertainties and their causes. If these uncertainties cannot be mitigated on the ground, they become candidates for on-orbit service mitigation, or (through upgrades) exploitation. Several existing examples of this kind of analysis are referenced.

4c) The evolving tradespace

The final approach to uncertainty is to consider its evolution with time, and the corresponding possibility that the design can evolve as the situation changes. As time passes, some uncertainties are reduced (i.e. things that were not know become known) while others may become larger, or evolve such that, for example, a future mean value turns out to be outside of the initially expected range.

The use of real options techniques to allow the hedging of future risks by investing in chance to react at some time in future is reasonably developed. Its impact on tradespace analysis is to add an additional dimension to the uncertainty calculations (time), and several additional complications to the design vector (future upgrade paths, and investments in options that may simplify these upgrades). Finally, in a rough analogy to the use of reliability as an "attribute" representing the possible degradation of the performance, an attribute or attributes of "flexibility" may be desired. This would simplify the representation of the collected system attributes' ability to remain near-optimal as user needs, technologies, or other uncertain factors changed.

There is not a "one-size fits all" solution (yet) to this challenge, but several cases are explored which provide some guidance for how to implement analyses of evolving tradespaces. The work of Durleth,[xi] Roberts,[xii] and Nichiani[xiii] are used as examples in representing flexibility on the tradespace. A final use of the spacetug example illustrates a possible generalization of the method.

[i] Some text modified from McManus, H. L. and Schuman, T. E., "Understanding the Orbital Transfer Vehicle Trade Space," AIAA Paper 2003-6370, Sept. 2003.

[ii] Galabonva, K., Bounova, G., de Weck, O. and Hastings, D., "Architecting a Family of Space Tugs Based on Orbital transfer Mission Scenarios," AIAA paper 2003-6368, Sept. 2003.

[iii] Ulrich, Karl T., and Steven D. Eppinger. 2000. *Product Design and Development, 2nd ed*. New York: Irwin/McGraw-Hill.

[iv] Koo, Benjamin H-Y, :A Meta-Language for Systems Architecting," Doctoral Thesis in Engineering Systems, Massachusetts Institute of Technology, January 2005.

[v] Rebentisch, E;, "Value-Based System of System Development," AIAA Infotech Conference, Sept, 2005.

[vi] McManus, H. L. and Hastings, D. E., "A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems." Fifteenth Annual International Symposium of the INCOSE, Rochester, NY, July 2005.

[vii] Benjamin, J. L., and Paté-Cornell, M. E., "A Risk Chair for Concurrent Design Engineering: a Satellite Swarm Illustration," *Journal of Spacecraft and Rockets*, Vol. 41, No. 1, 2004, pp. 51-59.

[viii] Lotov, A., Bushenkov, V., and Kamenev, G., *Interactive Decision Maps: Approximation and Visualization of Pareto Frontier*, Kluwer, 2004, Norwell, MA

[ix] Walton, M. A, and Hastings, D. E., "Applications of Uncertainty Analysis Applied to Architecture Selection of Satellite Systems" *Journal of Spacecraft and Rockets*, Vol. 41, No. 1, Jan.-Feb. 2004, pp. 75-84.

[x] Rjabally, E., Snape, S., Whittle, S., and Sen P., :Acknowledging Uncertainty in the Provision of Defene Capability: Insights from Literature," Fifteenth Annual International Symposium of the INCOSE, Rochester, NY, July 2005.

[xi] Derleth, Jason E., "Multi-Attribute Tradespace Exploration and its Application to Evolutionary Acquisition," Master's Thesis in Aeronautics and Astronautics, Massachusetts Institute of Technology, June 2003.

[xii] Roberts, Christopher J., "Architecting Evolutionary Strategies Using Spiral Development for Space Based Radar," Masters Thesis in Technology and Policy, Massachusetts Institute of Technology, June 2003.

[xiii] R. Nilchiani and D. Hastings. "Measuring Flexibility in Design of an Orbital Transportation Network,"AIAA-2003-6367, AIAA Space 2003 Conference and Exposition, Long Beach, California, Sep. 23-25.

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